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Finite element based model predictive control for active vibration suppression of a one-link flexible manipulator

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ABSTRACT

This paper presents a unique approach for active vibration control of a one-link flexible manipulator. The method combines a finite element model of the manipulator and an advanced model predictive controller to suppress vibration at its tip. This hybrid methodology improves significantly over the standard application of a predictive controller for vibration control. The finite element model used in place of standard modelling in the control algorithm provides a more accurate prediction of dynamic behavior, resulting in enhanced control. Closed loop control experiments were performed using the flexible manipulator, instrumented with strain gauges and piezoelectric actuators. In all instances, experimental and simulation results demonstrate that the finite element based predictive controller provides improved active vibration suppression in comparison with using a standard predictive control strategy.

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1. Introduction

Increasingly, lighter components are utilized in many applications such as automobiles, aircraft, and space structures. In space applications, structures such as space trusses and manipulators are made of lightweight materials allowing high speed and lower power consumption operations [1]. These structures are characterized by having very low damping and natural frequencies. Therefore, they are susceptible to unwanted vibrations during its motion. In the case of manipulators, these vibrations constitute persistent disturbances that affect the end effector trajectory.

The methods used to suppress the unwanted vibrations include passive control and active control. The passive control method consists of adding passive material on the structure in order to change its dynamic characteristics such as its stiffness and damping coefficients. Shunt damping is a type of passive vibration control using masses, dampers, springs and piezoelectric transducer to dissipate mechanical energy. Moheimani [2] provides a comprehensive survey of mechanism and application issues of piezoelectric shunt damping. Behrens [3] and Naoto [4] describe applications of using electromagnetic shunt damping. The passive vibration control system has its advantages as it is relatively simple to apply, has good stability and has proven to be successful in the areas of transportation vehicles, rotating machines, helicopters and many other industries. However, the passive control technique is ineffective for low frequency vibration. The passive devices in the control system can be relatively large and are designed to meet specific structural characteristics. In other words, the passive method tends to be characterized by a lack of controller robustness to system uncertainties and changes in structural dynamics. In addition, passive vibration control usually leads to an increase in the overall weight of the structure, which makes it less transportable and functional. These factors limit the usefulness of passive control method in lightweight flexible structures.

The limitations of the passive techniques have led to the development of active vibration control techniques [5]. These techniques are more suitable in cases where the system properties or the excitation nature may vary with time. In principle, the active control system employs actuators to supply energy that opposes or counteracts the existing unwanted energy. This results in reducing the structural vibrations. One of the advantages of an active system is that it can be readily applied and modified by control algorithms in order to meet some specified requirements. In flexible manipulators, the vibrations can be actively suppressed by controlling the joint motions. However, using the joint to control the vibrations of the flexible link adds constraints on the possible speeds and trajectories of the flexible manipulator. Other techniques involve the application of smart materials featuring distributed actuators and sensors. These actuators have the advantages of mechanical simplicity, small volume, lightweight, and efficient conversion between electrical energy and mechanical

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Nomenclature

δ	adjustment parameter
ζ	modal damping coefficient
θ	joint angle
λ	tuning parameter
ρ	material density
ϕ	mode shapes
ω	natural frequency
Δu	control move vector increment
Ξ_c^n	shape function of the nth PVDF film
Ψ_{Vi}^n	modal coefficient of PVDF
a_i	step (or impulse) response value
d_{31}	transverse piezoelectric charge to stress ratio
$\mathbf{e}$	error vector
k_θ	potentiometer encoder gain
k_u	motor torque constant
m_{ii}	elements of mass matrix
n_s	number of PVDF sensors
n_u	control horizon
q	modal coordinates
r	axial location
s	desired trajectory of motor position or tip displacement
u	control move vector
v	beam velocity
v_m	control voltage applied to the motor
v_p^n	control voltage applied to the nth PZT actuator
x	state vector
y	system output vector
$\hat{y}$	predicted process profile
z_c	distance from the neutral axis of the beam to the piezoelectric film
z^{-i}	backward shift operator in Z-transform
A	controller dynamic matrix
B_s	input matrix
C_c	capacitance of the piezoelectric film
C_s	output matrix
D	disturbance
E	vector of future errors
F_{Pi}^n	generalized nth PZT force for the ith mode
H_s	modal damping matrix for structure
H_{ps}	modal damping matrix for structure and PZT
J	controller objective function (or performance index)
J_h	motor-fixture inertia
P	controller predictive horizon
Q	weighting matrix for error vector
Q_s	generalized force vector
R	weighting matrix for control move vector
V_{oc}^n	open circuit voltage of nth PVDF patch
V_θ	potentiometer voltage signal

energy [6–11]. Crawley and De Luis [8] first introduced the idea of using piezoelectric (PZT) actuators as elements of smart structures. They derived the static and dynamic models for segmented piezoelectric actuators surface mounted or embedded in the flexible structures. Based on this introduction, Vaz [12] simplified the piezoelectric film actuator and sensor equations for easier implementation. A large amount of research [13–15] has demonstrated that the active approach using piezoelectric materials is effective in vibration control of flexible structures.

Finite element modelling (FEM) has been used to model flexible mechanisms with good success. The scheme has become quite useful as a means of obtaining accurate results. In the case of multi-link flexible manipulators having both revolute and prismatic joints, it was demonstrated that a finite element model required fewer computations for realtime control [16]. The control combined a nonlinear decoupling approach for large motions of robot with an LQR scheme that provided active damping of vibrations approaching the final motion of the links. Another seminal study demonstrated that effects of damping and joint dynamics can be incorporated in FEM with good comparisons to experimental data for a single link flexible manipulator [17]. Earlier studies by [18] modelled a flexible one-link manipulator using the FEM. In this case, a lower order linear quadratic compensator provided satisfactory control performance for controlling the end effector position with variable payloads.

Model Predictive Control (MPC) has been successfully applied to systems that are multi-variable and have a relatively high degree of non-linearity, providing effective and robust control performance [19–21]. The superiority of predictive control over many control schemes is that it is capable of predicting the future dynamic behavior of the system under control using a model derived from open loop tests or from analytical models. These predictions are then used to evaluate the magnitude of the current control actions. A survey of various MPC schemes and industrial developers [20] of control algorithms clearly demonstrates MPC as the advanced control strategy of choice for wide ranging complex nonlinear applications in manufacturing, aerospace, robotics and many others. Other schemes for handling nonlinearities can have complex control structures [22], in this case controlling a DC motor system with deadzone characteristics. In the case of disturbance rejection, standard MPC can reject disturbances, however, control performance degrades based on the complexity of the disturbance dynamics and the application the controller is subjected to. Investigations by [23–26] demonstrated the effectiveness of using disturbance observers for applications such as a grinding mill, systems with deadtime, hypersonic vehicles and static var compensators. These schemes provided improved closed loop performance when integrated with standard MPC.

The literature on MPC as an effective vibration reduction strategy on flexible systems is very limited [27]. The first attempt to utilize an MPC controller for active vibrations suppression on a flexible rotating one-link manipulator was reported by Hassan et al. [28] and later suggested to be so by [27]. The system model is constructed through performing open-loop step excitation tests on the flexible system. This strategy proved successful in actively suppressing the manipulator vibrations. These initial results strongly demonstrate that MPC can effectively suppress vibration on a flexible beam. Motivated by the first success of MPC application, Boscariot et al. [27] utilized MPC to control a four-link closed chain mechanism in simulation, positioned on a horizontal plane and driven by a single torque controlled electric motor. A more recent investigation by [29] using a single link flexible manipulator for closed loop vibration suppression demonstrated MPC superiority over an LQR scheme. The scheme used the standard constrained MPC for predicting the dynamic response of the flexible manipulator without other more involved forms such as FE modelling. Other schemes such as variable structure sliding mode control (VSSMC) described by [30] have been used with good success for controlling vibration on a flexible link beam. Due to the inherent chattering problems using VSSMC on very lightly damped systems, the strategy employed using a relatively large sampling period and lower controller gains.

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